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PART 3

INVITED PRESENTATIONS

Arctic Off-Shore Exploration Structures
A Geotechnical Perspective

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1.0 Introduction

Since 1969, 142 exploratory wells have been successfully drilled in the Beaufort Sea (Masterson, et al; 1991). Of this total, approximately 100 wells have been drilled from a variety of islands and bottom-founded structures in water depths up to 32 m (Figure 1). The remaining wells have been advanced from floating structures in water depths up to 67 m.

The marine environment in the Arctic is characterized by sea ice cover for approximately 9 months of the year. The design of bottom-founded structures, from which drilling is performed during the winter months, is dominated by the requirement to resist forces imposed by this ice. This requirement becomes more critical in the "shear" zone, which is the transition zone between the land fast ice zone and the polar ice pack (i.e., beyond approximately 20 m water depth).

The variety of bottom-founded structures utilized has ranged from sandbag retained islands through to fully mobile bottom-founded structures. The diversity includes sacrificial beach islands, ice islands, gravel islands, caisson-retained islands and caisson/berm structures. The design and operation of these structures has been largely governed by geotechnical considerations. This paper reviews the evolution of the structures from this perspective. Based on this review, the paper concludes with an overview of past and present concepts for production structures.

2.0 Surficial Geology of the Beaufort Sea

The exploration area relevant to this paper includes both the Canadian and US portions of the Beaufort Sea continental shelf. The surficial geology east of Herschel Island (i.e., Canada) is more complex than to the west due to the dominance of the Mackenzie Delta. A geologic model has been developed for this area (O'Connor & Associates, 1980) which divides the shelf into nine physiographic regions, based on the combination of seafloor bathymetry, sediment types and the paleotopography of the most recent unconformity. The nine regions consist of five plains (or plateaus) separated by four troughs (or channels).

The troughs (channels) are generally characterized by fine-grained weaker soils. The plains (plateaus) in some instances contain relic sand ridges which have been the primary source of borrow material for island construction in the Canadian Beaufort Sea.

The continental shelf of the Alaskan Beaufort Sea is a seaward extension of the Arctic Coastal Plain. Sediments of the shelf consist of clay, silt, sand and gravel with the major constituent being silt and clay. Sand and gravel are more common in the near shore and shallow water off-shore. Sources of sand and gravel may appear as shoals, sand ridges, lag deposits and as seafloor sediments. The soils in the Alaskan Beaufort Sea are generally competent, although weak soils with shear strengths less than 50 kPa are present in some areas. These weak soils are generally limited to a thin surficial veneer typically less than a metre thick, or a buried layer less than a few metres thick.

The seafloor is considered flat on a regional basis. However the micro- topography is characterized by sharp relief as a result of ice ridge gouging. Elevations may vary locally over a range of 0.6 m to 2.4 m or more, particularly in water depths of 15 m to 25 m. This ice gouging has remoulded the uppermost soils and reduced their strengths.

3.0 Structure Types

Apart from the truly mobile units (i.e., those requiring no on-site construction), almost every "structure" has had its unique aspects. However, they can be divided into general categories and the seven listed below have been chosen to broadly classify the structures utilized to date (see Tables 1 and 2).

- Sandbag Retained Islands - 14 wells (13 "structures"). Maximum water depth of 7.0 m.
- Sacrificial Beach Islands - 12 wells (11 "structures"). Maximum water depth of 18.6 m.
- Ice Islands - 5 wells. Maximum water depth of 7.6 m.
- Gravel Islands - 46 wells (30 "structures"). Maximum water depth of 14.6 m.
- Caisson Retained Islands - 14 wells (8 locations). Maximum water depth of 32 m.
- Water Ballasted Caisson on Berm - 2 wells. Maximum water depth of 31 m.
- Mobile Bottom-Founded Structures - 7 wells (6 locations). Maximum water depth to date of 21 m.

Each of these structures is described below, with emphasis on the geotechnical aspects.

3.1 Sandbag Retained Islands

A sandbag retained island is one where a ring dyke of sandbags is placed on the seafloor to retain the fill. The purpose of the sandbags is to retain marginal fill materials and hence, achieve steeper islands slopes and to protect against wave attack. The geotechnical design considerations include slope failure, edge failure (a local passive failure due to the ice load), truncation failure (decapitation) and bottom sliding. Fill quality has not been a major design issue. The criterion has been to utilize fill of sufficient quality to support the drilling package. Borrow sources have included clam shelled local seabed materials and soils barged to the site from a remote submarine borrow pit. An example of the design of a sandbag retained island is provided by Riley (1975).

3.2 Sacrificial Beach Islands

Sacrificial beach islands have flat beach slopes (1:15 to 1:25) which are intended to attenuate wave energy and provide an erosion buffer, thus protecting the island top from wave attack. This type of island is usually constructed when the island is located near a large borrow source, since a large amount of fill is required. The major advantage of a sacrificial beach island is the reduced requirements on slope protection which is both costly and difficult to construct. Barge hauling of fill from a distant source is usually prohibitive in terms of cost and construction time.

The construction method for a sacrificial beach island is simple. The island fill is dredged and place hydraulically using plain suction dredges and floating pipelines.

The geotechnical performance of these fills is difficult to quantify owing to a number of factors. First, the acceptance criteria for borrow material have been set only to ensure the dissipation of pore pressures built up during construction. The quality of the placed fill has not generally been verified. Second, no attempt is made to achieve steep slopes. Flat slopes are desirable to dissipate wave energy. A geotechnical "failure" of a locally steep slope during construction has not been considered a failure but, rather, a part of the construction process. Further, such a "failure" would be difficult to distinguish from slope flattening due to wave erosion. However, there are several observations which indicate that liquefaction "failures" have occurred. Third, because these islands have been situated in the land fast ice region and have generally been surrounded by large rubble fields, it is likely that they have not experienced significant horizontal shear loads.

The very flat side slopes has precluded the economical use of this approach at deeper water sites. Volume increases exponentially with water depth. Geotechnical considerations related to the construction of two sacrificial beach islands are outlined by Shinde, et al (1986).

3.3 Ice Islands

Spray ice islands have become a fairly routine option for prospects located in favourable water depths and ice regimes. The controlling issue is whether or not adequate drilling time can be provided following completion of island construction. The major advantage of such islands is the ready availability of the construction material and the subsequent natural decay.

Apart from the requirement for global sliding stability, a spray ice structure introduces unique considerations, as it is made of a material that is significantly weaker than the sea ice which surrounds it. The time-dependent behaviour becomes an important operational consideration. Island settlement during drilling, as well as lateral deformations associated with relatively low levels of load caused by pressure build-up and/or movement in the surrounding ice sheet, must be considered. The design and construction of the Mars Spray Ice Island is described by Funegard, et al (1987).

3.4 Gravel Islands (Armoured - Slope Islands)

The advantages of using good quality gravel for island construction is the reduced fill quantities resulting from steep slopes (1:3 to 1:5). These islands have been the most common type in the Alaskan Beaufort Sea where abundant sand is not available and non-U.S. dredges are not permitted to work. The gravel has been obtained from on-shore sources and either dumped on site by barges during the summer or, more commonly, hauled directly to the island site in winter via an ice road. The source of this gravel is described by Schlegel and Mahmood (1985). It is relatively abundant east of the Colville River to the Canadian border. These islands have been protected by a revetment, normally consisting of large sandbags overlying filter cloths, although other types of armour have been used. The disadvantage of this island type is that the placement of the slope protection can be very time consuming, especially below water.

The geotechnical design issues for this island type are similar to those for sandbag retained islands, although slope failure obviously becomes more critical. Consideration can also be given to strength gain at the seabed interface due to consolidation between the time of placement and the time of maximum anticipated ice load. Thaw settlement of loose frozen fill placed in the water, especially the underwater portion, has to be considered. The engineering and construction of Mukluk Island in 14.6 m of water is described by Ashford (1984).

3.5 Caisson and Caisson Retained Islands

The 1980's saw the introduction of a number of hybrid exploration islands designed primarily to reduce the fill volume requirements at deeper water locations. Four water line penetration systems were developed:

- Canmar's concrete caisson system, the "Tarsiut caissons" (1981) (Fitzpatrick and Stenning, 1983).
- Canmar's single steel drilling caisson, the "SSDC" (1982) (Fitzpatrick, 1983).
- Esso's segmented steel caisson, the "CRI" (1983) (de Jong and Bruce, 1978).
- Gulf Canada Resources Ltd.'s monolithic annular caisson the "Molikpaq" (1984) (Bruce and Harrington, 1982; McCreath et al, 1982).

Although the details of each system vary, deployment of all systems has commenced with the building of a steep-sided (1:6 - 1:8) sub-sea sand berm on which the caisson is placed. As most proposed sites did not possess suitable local borrow material, trailing suction hopper dredges were introduced to transport sand from remote locations. Trailing suction hopper dredges pick up material from a submarine borrow source by dragging an arm along the seabed. They are capable of carrying up to 8,000 m^3 of sand per load. Apart from the SSDC, which was ballasted onto the berm with water, all the systems required backfilling of a central core with sand.

The deployment of these new systems demanded a significant increase in design effort from that required for the previous more rudimentary structures. The basic design issues are not appreciably different from those of any other major civil work. However, the unique environmental loads and the restrictions in construction season length, construction plant and borrow materials created some major challenges. The geotechnical components included site investigations, stability and deformation analyses, quality assurance programs and performance monitoring. The location of these structures, in the unstable "shear" zone, precluded the prior technique of conducting the investigations from the land fast ice surface in the spring using conventional terrestrial methods. Hence, marine supported operations were employed during the short open-water season. These operations also incorporated the routine use of insitu testing techniques, including the cone penetration test (CPT), vane shear tests and the self-boring pressure meter (Ruffell et al, 1985). The introduction of the trailing suction hopper dredges required the identification of acceptable sand deposits at or close to the surface. This was accomplished by conducting regional shallow seismic surveys in conjunction with extensive shallow boring programs. Beyond static stability issues, the requirement to place a heavy structure on a berm capable of resisting the large horizontal ice loads that were anticipated in the "shear" zone required that the issue of dynamic stability be addressed. The consequences of liquefaction failure of such islands are potentially catastrophic. The criterion first proposed was based on a pseudo-static approach which called for a gradational specification to inhibit pore pressure generation and a relative density which ensured dilative behaviour during shear. Use of the "steady state" method (Poulos, 1981) was subsequently successfully employed. There are, however, problems related to insitu determination of sand state (Sladen and Hewitt, 1989; Sladen, 1989).

In order to assess structure performance and, in particular, to develop "alert" criteria based on monitoring of instrumentation, it is necessary to make an accurate prediction of load deformation behaviour under ice loading. For these structures resting on sand berms, the non-linear elastic hyperbolic model of Duncan and Chang (1970) was adopted. Fill quality assurance and insitu density evaluation became a significant component of construction operations. This involved monitoring of material loaded into the dredges, post placement coring and CPT testing. This also implied that a material specific correlation between tip resistance and density had to be developed (Berzins and Hewitt, 1984).

A number of instruments were employed to assess the response of the structures and foundations to ice loads. The primary monitoring method utilized manual and in place inclinometer systems. Other instruments and methods included piezometers, total pressure cells, extensometers, tilt meters, settlement systems and conventional survey methods. The performance of these "caisson" structures has generally been acceptable (Blanchet, et al, 1991). Actual ice loadings have been well below design values and therefore the corresponding deformations have been small (Blanchet, et al, 1991).

3.6 Mobile Bottom-Founded Structures

The most recent generation of off-shore exploration structures developed for use in the Beaufort Sea have been mobile bottom-founded structures. Although similar in some respects to gravity base structures that have been used widely in non-Arctic oceans, they have some unique characteristics that have been dictated by the need to resist high horizontal ice loading. Two such units have been built and deployed, the Concrete Island Drilling System, 'CIDS', operated by Global Marine Ltd. (Masonheimer, et al, 1986) and the steel SSDC/MAT system operated by Canadian Marine Drilling Ltd. (Hewitt, et al, 1988). The latter was a development of the SSDC caisson that had previously been based on a hydraulic fill berm. For the new system, the berm was replaced by a specially fabricated steel base or mat which was mated to the SSDC.

These systems offer two major advantages over the earlier units. Firstly, they can operate in relatively deep water (up to 17 m for the CIDS and 25 m for the SSDC/MAT) without the need for an artificial berm or sand core. This avoids the cost of berm construction, the need for suitable berm material and the problems associated with decommissioning. In the Canadian Beaufort Sea, where sand had been the traditional construction material, the need to undertake costly densification to eliminate the risk of liquefaction was also avoided. The second advantage is that there is no need for site preparation.

The base design for these structures is governed by geotechnical considerations. The features of the surficial sediments in the Beaufort Sea have been described previously. Some typical shear strength profiles are illustrated in Figure 2. The structures develop high lateral load resistances in these conditions by means of their large bases which incorporate a grid of horizontal strip anchors. These 'skirts' project from the base and are forced into the seabed when the unit is ballasted down (Figure 3). As a result, they accommodate some unevenness in the seafloor and efficiently develop lateral resistance. The components of lateral resistance are passive resistance and base friction. The depth of penetration of the skirts is controlled by the soil strength in relation to the available ballast weight. For relatively stiff soils, the penetration is low and the majority of resistance is derived from the skirt tips. For soft soils, the skirts can penetrate until the base comes into contact with the soil. In such uses, the passive resistance is the major component.

As with caisson islands, geotechnical assessments of these structures must address not only the overall stability but also deformations under ice loading. Detailed predictions of foundation deformation have made use of non-linear finite element analysis (Sladen, et al, 1990). These are important, not only from the viewpoint of serviceability but also with respect to monitoring. As direct measurement of ice loads is impracticable, geotechnical instrumentation, predominantly in place inclinometers, has been the primary means of setting alert criteria. Foundation deformations can be related to ice load level and hence to margin of safety.

More recently, the use of geotechnical instrumentation in conjunction with detailed predictions of deformation, have been explored as a means of measuring ice loads from observed ice events and hence assisting in the rationalization of ice design criteria. Although estimated ice loads are approximate, results have been encouraging and the method is arguably as reliable as any other method of estimating ice load (Blanchet, et al, 1991).

Table 3 (from Blanchet, et al, 1991) shows the results of ice load estimations for six sites (four caisson locations and two SSDC/MAT locations). For comparison, the range of ice loads measured by other methods is also indicated. As can be seen, estimated ice loads have all been less than 200 MN. This is significantly lower than design loads that would have been predicted for the ice events, based on available data during the early stages of off-shore development in the Beaufort Sea. The accommodation of ice loads is one of the major engineering challenges that must be met if off-shore production facilities are to be developed in the Arctic. Detailed geotechnical modelling and instrumentation have provided valuable data that have shown that traditional design ice loads were very conservative. By providing a rational basis for lower design ice loads, one of the major potential barriers to development has been reduced.

4.0 Summary

Exploratory drilling for hydrocarbons has been conducted from off-shore "structures" in the Beaufort Sea for over twenty years. The initial "structures" consisted of a variety of earth fill islands in very shallow water depths. In the late 1970's, this concept, with variations and refinements, was extended into deeper waters. In the early 1980's, composite caisson/earth fill structures were introduced. The limited data base on ice at that time lead to high design ice loads with the result that massive structures were required. These large earth fill structures were, however, associated with problems such as liquefaction and decommissioning.

By the mid-1980's, with the accumulation of considerable design and operational experience, it became feasible to utilize fully mobile structures. These units develop lateral resistance by mobilizing the shear strength of relatively competent soils below the seabed surface. Today, exploratory drilling is efficiently conducted from such structures on a routine basis.

5.0 Production Structure Concepts

When the Beaufort Sea - Mackenzie Delta Region Environmental Impact Statement (EIS) was prepared in 1982, a number of possible production structure concepts were tabled. These are briefly described as follows.

5.1 Dredged Islands

Dredged islands were proposed as production platforms in shallow water (0 to 20 m). These were seen to be similar to sacrificial beach islands with slope protection to prevent erosion. They would also extend further above the surface to minimize run-up of waves during fall storms. Slope protection would be provided by rock and gravel or man-made materials.

5.2 Caisson-Berm Island (Caisson Retained Island)

The caisson-berm production platform would initially be constructed as an exploration platform. If hydrocarbon discoveries demonstrated sufficient reservoirs, production could be undertaken at the site by expanding the island.

5.3 Gravity Structures

A gravity structure was envisioned to be somewhat like some of those used in the North Sea. Relying on its own weight to anchor the platform in place, the caisson was seen to be constructed of concrete and would be about 90 m in diameter at the water level. The advantage of this structure was that it is relatively simple and could be totally fabricated in the south. The ability of the structure to resist the limit stress forces associated with an ice island interaction was the subject of on-going studies. A variation of this concept was to place the gravity structure on top of a dredged berm.

5.4 Monocone Structure

This proposed steel or concrete structure was a variation of the monopod structures used in Cook Inlet, Alaska. The structure would be anchored to the seafloor with piling or by its own weight. It was felt that this design could safely resist most of the ice forces which could be exerted upon it by ice features in the Beaufort Sea. However, its resistance to loads from a large ice island was questioned.

5.5 Arctic Production and Loading Atoll (APLA)

The island building technology developed at that time was seen to be applicable to building production islands even in deep water. The largest concept for off-shore platforms was called the Arctic Production and Loading Atoll (APLA). A number of alternate concepts were proposed. One concept consisted of two islands forming a protected harbour or lagoon. The islands were designed to withstand the forces associated with ice island impacts.

The APLA would be built from granular material, dredged from borrow sites as near as possible to the APLA site. The type of dredgers used would be dependent on the water depth of the APLA, the distance to the borrow site and the time allocated to build the APLA. If an APLA were eventually built at a site like Kopanoar (60 m water depth), approximately 100 million cubic metres of material could be required and a quantity of clay would first have to be removed from the site. This work would require specially designed dredges because of the water depth and the long haul from likely borrow sites. Locations in shallower water depths would require considerably less borrow material and in some cases, where bottom conditions permit, stationary suction dredges could be utilized. A site in 25 m of water would require approximately 30 million cubic metres of material.

Since the compilation of the EIS, three events have transpired. Firstly, significant research efforts applied to the understanding of the ice environment and ice mechanics has resulted in a better understanding of the environmental forces. It now appears feasible that the design global ice load could be set in the order of 100,000 tonnes. Ten years ago the massive structures envisioned were designed to resist loads ten times these values.

Secondly, the typical development scenario of a decade ago was a megaproject based on regional reserves in the order of 1 - 2 billion barrels of liquids. Discoveries to date total several million barrels which do not support the capital costs of APLA type structures. Lastly, operations and research has shown that steel plated structures can be designed and constructed with capital costs that show favourable economics based on discoveries to date. Today's concept for a production platform would consist of a water ballasted steel plated structure, potentially sitting directly on the seabed. Where foundation conditions are unfavourable, excavation of the weak soils and replacement with granular material would be required.

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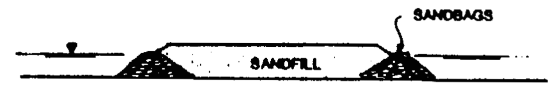
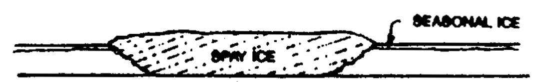
TYPE	MAX. WATER DEPTH	NUMBER OF LOCATIONS	DESCRIPTION	SCHEMATIC ILLUSTRATION
Sandbag Retained Islands	7	13	Ring dyke of sandbags retaining internal hydraulic fill E.g. Adgo F-28,Ellice L-39	
Sacrificial Beach Islands	19	11	Hydraulically placed sand fill with flat-side slopes E.g. Alerk P-33 ,Immerk B-48	
Ice Islands	8	5	Seasonal ice thickened by flooding or spraying until base in contact with seabed. E.g. Mars, Angasak	
Gravel Islands	15	30	Coarse fill placed usually by barge dumping or trucking on ice. Erosion protection usually provided E.g. Pullen E-17, North star	

TABLE 1 NON - CAISSON ISLANDS

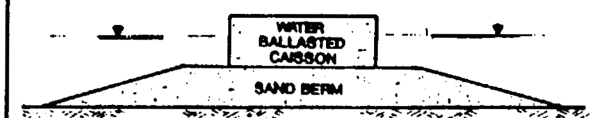
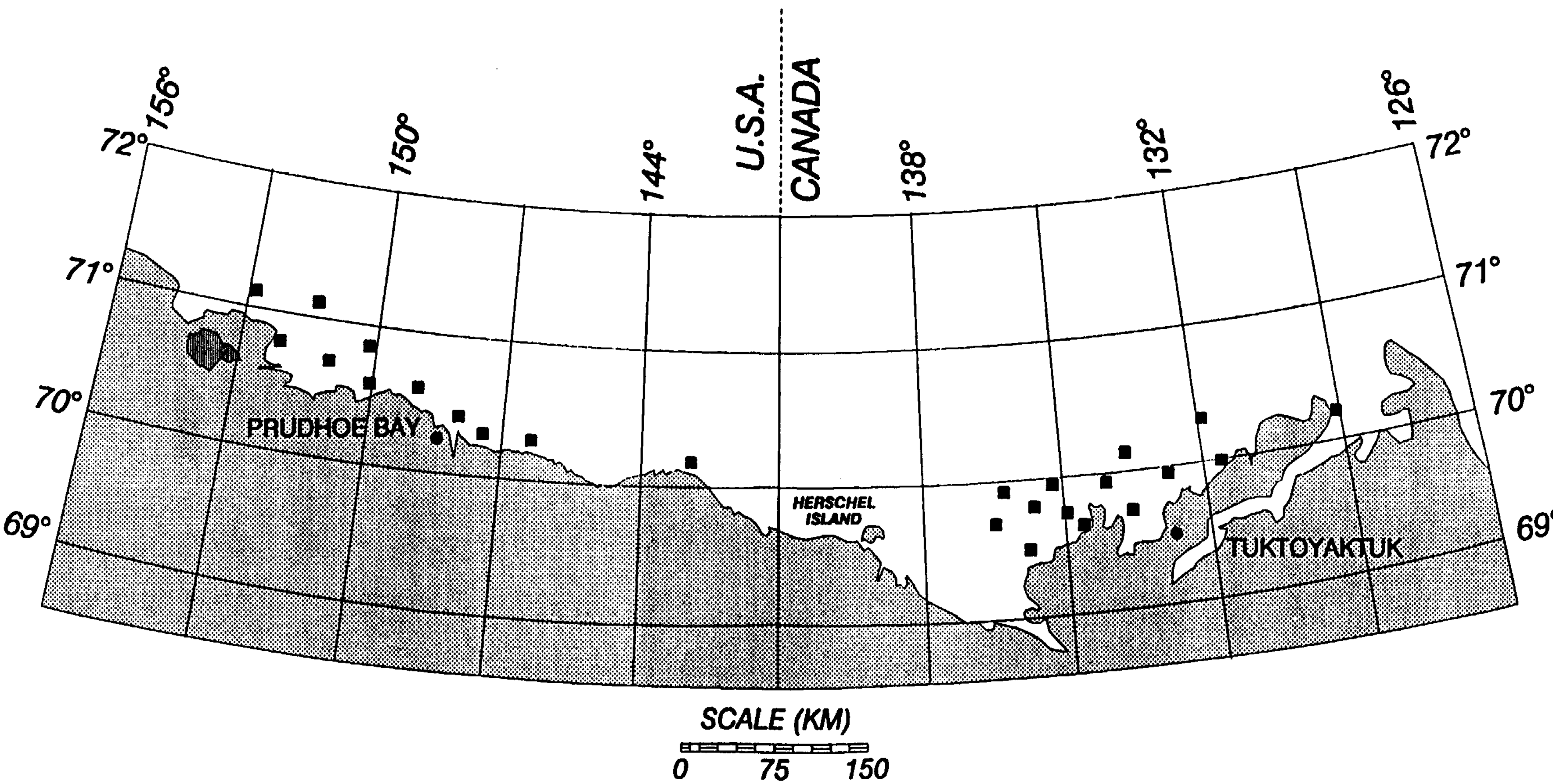
TYPE	MAX. WATER DEPTH	NUMBER OF LOCATIONS	DESCRIPTION	SCHEMATIC ILLUSTRATION
Caisson Retained Islands	21m + Berm Height	8	Similar to sandbag retained island but caisson used to retain fill allowing greater depth range E.g. Tarsiut Caissons, CRI, Molikpaq	
Water Ballasted Caisson/Berm	9m + Berm Height	2	Water ballasted caisson used in place of fill in wave and ice scour zone, placed on hydraulic sand berm. E.g.SSDC	
Bottom Founded Structures	25	6	Bottom founded structure , mobile and avoiding need for any fill berm E.g. CIDS, SSDC/MAT.	

TABLE 2 CAISSON ISLANDS

FIGURE 1

LOCATION OF OFFSHORE STRUCTURES BEAUFORT SEA



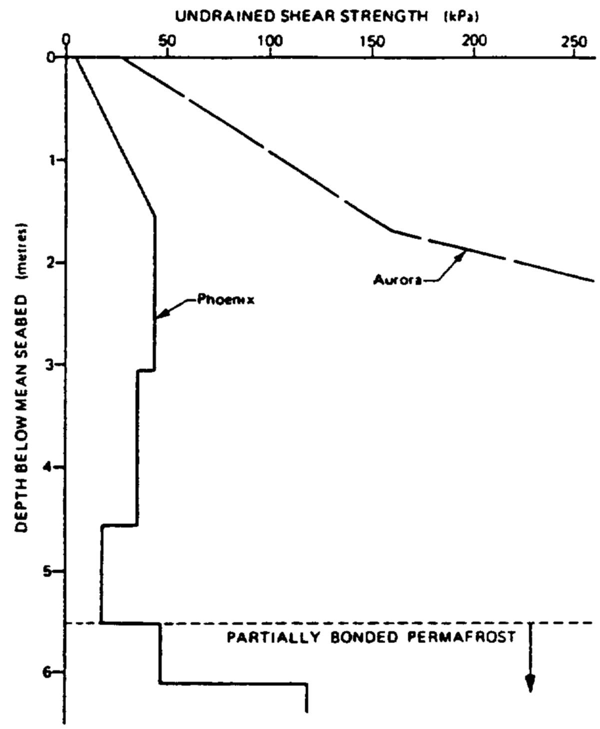


FIGURE 2

DESIGN UNDRAINED SHEAR STRENGTH PROFILES

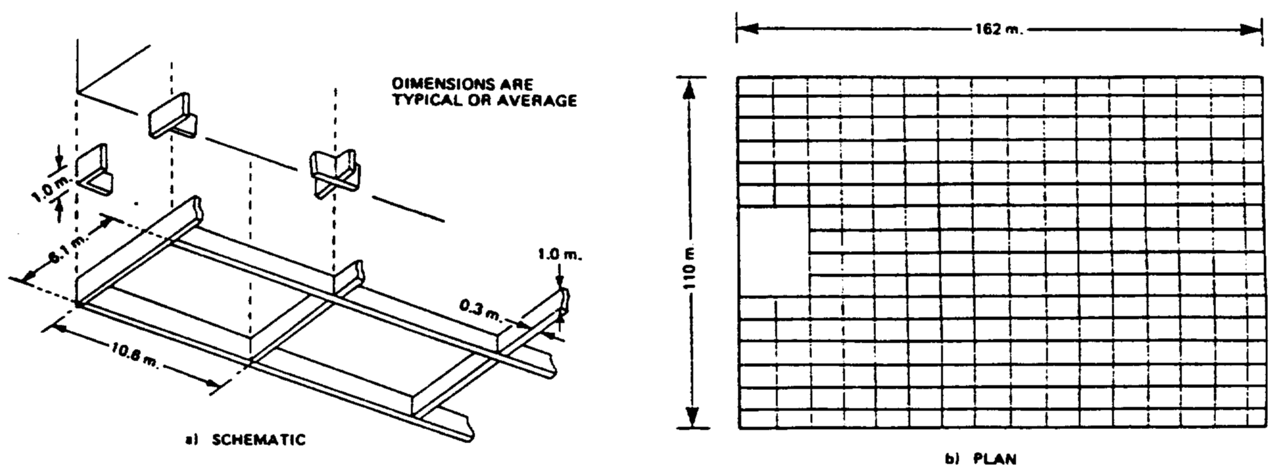


FIGURE 3

ARRANGEMENT OF BASE SKIRTS SSDC/MAT

Table 3

Case History	Maximum Interpreted Ice Load (MN)	
	From Ice Monitoring	From Geotechnical Response
Tarsiut	140	20
Uviluk	80 70 (June)	<30 N/A
Kogyuk	<100 (setdown) N/A 100 (June)	<100 <30 N/A
Amauligak	500+ (Jefferies & Wright) 230 (Blanchet)	<110
Phoenix	70	20
Aurora	<70	<35